Financial support from the Austrian National Bank (OeNB) grant no. 18611, Fundação para a Ciência e a Tecnologia grant no. UIDB/00315/2020 and from the European Union Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No. 721846, “Expectations and Social Influence Dynamics in Economics” is gratefully acknowledged.
Outline of the presentation

1. Motivation
2. An extended NK model
3. The asymmetric Phillips curve
4. Fitting micro and macro data with a small NK model
5. Conclusion
1 Motivation

2 An extended NK model

3 The asymmetric Phillips curve

4 Fitting micro and macro data with a small NK model

5 Conclusion
1. **Well established fact that NK models struggle to fit the shifts in the Phillips curve:**

\[ \hat{\pi}_t = \beta(\chi)E_t \hat{\pi}_{t+1} + \kappa(\theta, \chi, \cdot)\hat{y}_t + \chi \hat{\pi}_{t-1} + \varepsilon_t^s \]

2. **Solving the missing deflation and inflation in NK models:**
   - higher Calvo \(\rightarrow\) stickier prices / flatter NKPC (Del Negro et al., 2015);
   - \(\theta\) \(\rightarrow\)\(\kappa\)
   - large autocorrelated cost-push shocks and indexation (Fratto and Uhlig, 2020; King and Watson, 2012);
   - \(\chi\) \(\rightarrow\)\(\beta\) and \(\kappa\)

3. We end up explaining inflation with shocks on inflation ....
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NK models and the shift in Phillips curve II

- Literature focuses on:
  - non-linear effects (Harding et al., 2022);
  - exogenous shift in price stickiness (Davig, 2016; Fernández-Villaverde and Rubio-Ramírez, 2007);
  - change in price updating behaviour (Del Negro et al., 2020; Costain et al., 2022).

- Point of departure, a combination of all of that:
  - \( \Rightarrow \) endogenous time-varying price-setting frequency \( \theta_t \).
Motivation for time variation in the Calvo I

- The Calvo probability $0 < \theta < 1$ can be interpreted as the exogenous share of unchanged prices at one period.
  - It is assumed to be a structural parameter (Fernández-Villaverde and Rubio-Ramírez, 2007), yet the estimated value has moved from $\theta \simeq 0.75$ to $\theta \simeq 0.9$ with post 2008 samples?

- Micro-data contradicts the static Calvo assumption (Blinder et al., 1998; Klenow and Kryvtsov, 2008; Nakamura et al., 2018).

- Pure state dependent pricing models struggle with empirical money non-neutrality (Nakamura and Steinsson, 2010; Costain et al., 2022).
Figure 1: Seasonally adjusted share of unchanged prices, $\theta_t$, in the US from price tags data changes weighted according to the 2000 household consumption basket based on Nakamura et al. (2018).
What we do

1. Implement a **time-varying price-setting frequency** in a NK model via the *Calvo law of motion*:
   - update or not $\mapsto$ discrete choice process;
   - decision is based on the *present values* of updating;
   - Time-dependent pricing with a flavour of state-dependence $\Rightarrow$ highly tractable!

2. Does this improve the NK model with regard to fitting the Phillips curve, macro and micro-data?
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Results

Our extended model:

1. generates an asymmetric Phillips curve which is:
   - steep during boom;
   - flat during bust;
2. is consistent with micro and macro-data;
3. can explain the shifts in the Phillips Curve without large cost-push shocks, high indexation or very sticky prices;
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How to approximate the resetting problem?


\[
\theta_t = \frac{\exp\left(\omega U_{t}^f\right)}{\exp\left(\omega U_{t}^f\right) + \exp\left(\omega (U_{t}^* - \tau + \varepsilon_{\theta})\right)},
\]

- \( \theta_t \): Share of non resetting firms;
- * is the index for the optimal resetting price;
- \( f \) is the index for the average old price;
- \( U_{t}^f, U_{t}^* \): Present values of the pricing decisions;
- \( \omega, \tau \): Intensity of choice and fixed cost of updating;
- \( \varepsilon_{\theta} \): AR(1) shock explaining the residual variation.

Consistent with state-dependent pricing models.
Calvo aggregation:

\[ P_t = \left( \theta_t P_{t-1}^{1-\epsilon} + (1 - \theta_t) P_t^* 1^{-\epsilon} \right) \frac{1}{1-\epsilon} \]  

Firm maximization problem (w/ linear production technology):

\[
\max_{P_t^*} \mathbb{E}_t \sum_{j=0}^{\infty} D_{t,t+j} \left( \prod_{k=0}^{j} \theta_{t+k} \right) \theta_t^{-1} \left[ \frac{P_t^*}{P_{t+j}} - \frac{\Gamma'_{t+j}}{P_{t+j}} \right] Y_{i,t+j} \\
\text{s.t. } Y_{i,t+j} = \left( \frac{P_t^*}{P_{t+j}} \right)^{-\epsilon} Y_{t+j}
\]

Firm’s FOC:

\[
p_t^* = \frac{\epsilon}{\epsilon - 1} \frac{\mathbb{E}_t \sum_{j=0}^{\infty} \left( \prod_{k=0}^{j} \theta_{t+k} \right) \theta_t^{-1} D_{t,t+j} \prod_{t+1,t+j}^\epsilon Y_{t+j} w_{t+j}}{\mathbb{E}_t \sum_{j=0}^{\infty} \left( \prod_{k=0}^{j} \theta_{t+k} \right) \theta_t^{-1} D_{t,t+j} \prod_{t+1,t+j}^{\epsilon-1} Y_{t+j}}
\]
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Figure 2: Asymmetric impulse responses to a positive or negative demand shock in the small-scale NK model. The shock is a ±2.5% shock at the discount factor.
**The Non-linear NKPC (Fair and Taylor, 1983)**

![Inflation and Output](image1)

(a) Inflation and Output

![Inflation and the Calvo](image2)

(b) Inflation and the Calvo

**Figure 3:** Simulated moments of the non-linear model under discount factor shocks.
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Objective: demonstrate the quantitative relevance of the mechanism.

We estimate the model using data for the US (GDPC1, PCE, FEDFUNDS) from 1964 to 2019.

Measurement equations are

\[
\begin{align*}
y_{t}^{obs} &= \hat{y}_{t} \\
\pi_{t}^{obs} &= 100 \times \ln(\bar{\pi}) + \hat{\pi}_{t}, \quad \text{where} \quad \bar{\pi} = 1 + \gamma_{\pi}/100 \\
r_{t}^{obs} &= 100 \times ((\bar{\pi}/\beta) - 1) + \hat{i}_{t} \\
\theta_{t}^{obs} &= \theta_{t},
\end{align*}
\]

Key novelty: Nakamura et al. (2018) micro-data for the last equation.
**Figure 4:** Historical decomposition, observed inflation, US data (1964-2019).

GASTEIGER AND GRIMAUD
## Relevance of the endogenous Calvo model

### Detailed moments

<table>
<thead>
<tr>
<th></th>
<th>(1964-2019 (full sample))</th>
<th>Filtered model</th>
<th>$\theta_t = \theta \ \forall t$</th>
<th>$\epsilon_t^\theta = 0 \ \forall t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_t$ mean</td>
<td>3.3665</td>
<td>3.2370</td>
<td>3.3926</td>
<td></td>
</tr>
<tr>
<td>$\pi_t$ median</td>
<td>2.6056</td>
<td>2.6782</td>
<td>2.6595</td>
<td></td>
</tr>
<tr>
<td>$\pi_t$ variance</td>
<td>5.3527</td>
<td>3.8370</td>
<td>5.4351</td>
<td></td>
</tr>
<tr>
<td>$\pi_t$ skewness</td>
<td>1.3271</td>
<td>0.8472</td>
<td>1.3343</td>
<td></td>
</tr>
<tr>
<td>$\text{corr}(\pi_t, \theta_t)$</td>
<td>-0.8443</td>
<td>0</td>
<td>-0.9844</td>
<td></td>
</tr>
<tr>
<td>$\text{corr}(\pi_t, \hat{\gamma}_t)$</td>
<td>0.0839</td>
<td>0.1442</td>
<td>0.0734</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Inflation moments and related statistics, filtered non-linear model and counter-factuals.
1 Motivation

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Conclusion

1. Assuming a **static Calvo share has limitations**;
2. We provide a model that approximates well the aggregate variation in price resetting;
3. The model is consistent with **micro-data and macro-data** dynamic;
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Thank you for your attention.

Questions? Comments?
In a simple linear production NK economy we have:

\[ U_t^x = E_t \sum_{k=0}^{\infty} D_{t,t+k} \left( \prod_{j=0}^{k} \theta_{t+j} \right) \theta_t^{-1} \]

\[
\begin{bmatrix}
Y_{t+k} \left( \frac{p_t^x}{(\Pi_{t,t+k-1} \Pi_t^{-1})} \right)^{1-\epsilon} - Y_{t+k} w_{t+k} \left( \frac{p_t^x}{(\Pi_{t,t+k-1} \Pi_t^{-1})} \right)^{-\epsilon} \\
\end{bmatrix}
\]

\[ = \left( p_t^{x1-\epsilon} \phi_t - p_t^{-\epsilon} \psi_t \right) Y_t^\sigma , \]

- \( \theta_t \): Share of non resetting firms;
- \( p_t^x \): Relative price;
- \( w_t \): real wage;
- \( \Pi_t \): is the cumulated inflation;
- \( \epsilon \): elasticity of substitution among goods;
- \( \phi_t \) and \( \psi_t \): numerator and denominator of the FOC of the optimal price decision.
Figure 5: The Calvo law of motion (black). The y-axis is the level of $\theta$ and the x-axis is the difference between the expected profit of not updating and updating the price.
Figure 6: Comparative statics: present value of real profits as function of relative price at different levels of output.
The negative relation between inflation and realized/expected Calvo (non-price resetting) share:

\[ \hat{\pi}_t = \alpha_1 \hat{y}_t + \alpha_2 \mathbb{E}_t \hat{\pi}_{t+1} + \alpha_3 \mathbb{E}_t \hat{\phi}_{t+1} + \alpha_4 \hat{\theta}_t + \alpha_5 \mathbb{E}_t \hat{\theta}_{t+1} + \varepsilon_t, \quad (4) \]

with \( \alpha_1, \alpha_2, \alpha_3, \alpha_5 > 0 > \alpha_4. \)
Aggregate demand: \[ Y_t^{-\sigma} \exp(\epsilon^d_t) = \beta \mathbb{E}_t \left\{ \frac{(1 + i_t)}{\pi_{t+1}} Y_{t+1}^{-\sigma} \exp(\epsilon^d_{t+1}) \right\} \]

Labor supply: \[ w_t = \exp(\epsilon^s_t) \chi N_t^{\phi} Y_t^\sigma, \]

Price setting freq.: \[ \theta_t = \frac{\exp(\omega U^f_t)}{\exp(\omega U^f_t) + \exp(\omega (U^*_t - \tau + \epsilon^\theta_t))}, \]

Value of firm: \[ U^x_t = \left( p_t^{x^{1-\epsilon}} \phi_t - p_t^{x^{-\epsilon}} \psi_t \right) Y_t^\sigma \quad \text{for} \quad x \in \{*, f\} \]

Opt. relative price: \[ p^*_t = \frac{\epsilon}{\epsilon - 1} \frac{\psi_t}{\phi_t} \]

\[ \psi_t = w_t Y_t^{1-\sigma} + \mathbb{E}_t \beta \theta_{t+1} \pi_{t+1}^{\epsilon} \psi_{t+1} \]

\[ \phi_t = Y_t^{1-\sigma} + \mathbb{E}_t \beta \theta_{t+1} \pi_{t+1}^{\epsilon-1} \phi_{t+1} \]
Av. relative old price: \( p_t^f = 1 / \pi_t \)

**Inflation:** \( 1 = (\theta_t \pi_t^{\epsilon-1} + (1 - \theta_t)p_t^{1-\epsilon})^{\frac{1}{1-\epsilon}} \)

**Price dispersion:** \( s_t = (1 - \theta_t)p_t^{*-\epsilon} + \theta_t \pi_t^{\epsilon}s_{t-1} \)

**Aggregate output:** \( Y_t = N_t / s_t \).

**Monetary policy:** \( \left(\frac{1 + i_t}{1 + \bar{i}}\right) = \left(\frac{1 + i_{t-1}}{1 + \bar{i}}\right)^\rho \)

\[\left(\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_{\pi}} \left(\frac{Y_t}{\bar{Y}}\right)^{\phi_y}\right)^{(1-\rho)} \exp(\epsilon_{r,t}^r),\]

**Cost-push shock:** \( \epsilon_t^s = \rho_s \epsilon_{t-1}^s - \mu_s u_{\epsilon^s,t-1} + u_{\epsilon^s,t} \)

**Other shocks:** \( \epsilon_t^j = \rho_j \epsilon_{t-1}^j + u_{\epsilon^j,t}, \)

where \( j \in \{d, r, \theta\} \),

with \( 0 \leq \rho_j, \rho_s < 1, 0 \leq \mu_s < 1 \) and \( u_{\epsilon^j,t}, u_{\epsilon^s,t} \sim \text{iid } \mathcal{N}(0, \sigma_j^2) \).
<table>
<thead>
<tr>
<th>Price setting</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega$  Intensity of choice</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>$\theta$  Calvo share</td>
<td>0.75</td>
<td>Galí (2015)</td>
</tr>
</tbody>
</table>

**Monetary authority**

| $\phi_\pi$  MP. stance, $\pi_t$        | 1.5     | Galí (2015)          |
| $\phi_y$    MP. stance, $Y_t$           | 0.125   | Galí (2015)          |
| $\rho$      Interest-rate smoothing     | 0       | -                    |
| $\pi$  Gross inflation trend            | 1.008387| Average log growth of PCE implicit price deflator, 1964-2019 |

**Preferences and technology**

| $\beta$  Discount factor               | 0.99    | Galí (2015)          |
| $\sigma$  Relative risk aversion       | 1       | Galí (2015)          |
| $\phi$    Inverse of Frisch elasticity | 0       | Ascari and Ropele (2009) |
| $\epsilon$  Price elasticity of demand| 9       | Galí (2015)          |

**Exogenous processes**

| $\rho_d$  Discount factor shock, AR(1) | 0.8     | illustrative purpose |
| $\rho_r$  MP shock, AR(1)              | 0.8     | illustrative purpose |

**Table 2:** Calibrated parameters (Galí, 2015) for dynamic simulations (quarterly basis)
<table>
<thead>
<tr>
<th>Price setting</th>
<th>Prior</th>
<th>Posterior 5%</th>
<th>Posterior 95%</th>
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<td>$\gamma_{\pi}$</td>
<td>$\mathcal{G}$</td>
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<td>.1</td>
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<td><strong>Preferences and technology</strong></td>
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<td>100($\pi_0/\beta - 1$)</td>
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<td>$\sigma$</td>
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<tr>
<td>$\rho_r$</td>
<td>$\mathcal{B}$</td>
<td>.5</td>
<td>.1</td>
</tr>
<tr>
<td>$\rho_\theta$</td>
<td>$\mathcal{B}$</td>
<td>.5</td>
<td>.1</td>
</tr>
</tbody>
</table>

**Log-likelihood**: -74.6242

**Table 3**: Estimated parameters of the augmented small-scale NK model (US: 1964-2019). $\mathcal{B}$, $\mathcal{G}$, $\mathcal{IG}$, $\mathcal{N}$ denote beta, gamma, inverse gamma and normal distributions, respectively.
Figure 7: Historical decomposition, observed Calvo share, US data (1964-2019).
### Table 4: Inflation moments and related statistics, filtered non-linear model and counter-factuals.

<table>
<thead>
<tr>
<th></th>
<th>Filtered model</th>
<th>( c_l^l = 0 \forall t )</th>
<th>( c_l^l = c_l^l = 0 \forall t )</th>
<th>( c_l^l = 0 \forall t )</th>
<th>( c_l^l = c_l^l = 0 \forall t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi_t ) mean</td>
<td>3.3665</td>
<td>3.3926</td>
<td>3.3725</td>
<td>3.4013</td>
<td>3.3195</td>
</tr>
<tr>
<td>( \pi_t ) median</td>
<td>2.6056</td>
<td>2.6595</td>
<td>2.7075</td>
<td>2.7123</td>
<td>2.9865</td>
</tr>
<tr>
<td>( \pi_t ) variance</td>
<td>5.3527</td>
<td>5.4351</td>
<td>5.2963</td>
<td>5.3741</td>
<td>3.1133</td>
</tr>
<tr>
<td>( \pi_t ) skewness</td>
<td>1.3271</td>
<td>1.3343</td>
<td>1.2980</td>
<td>1.3160</td>
<td>1.6055</td>
</tr>
<tr>
<td>( \text{corr}(\pi_t, \theta_t) )</td>
<td>-0.4065</td>
<td>-0.8359</td>
<td>-0.7240</td>
<td>-0.7240</td>
<td>-0.7240</td>
</tr>
<tr>
<td>( \text{corr}(\pi_t, \hat{y}_t) )</td>
<td>0.0839</td>
<td>0.0734</td>
<td>-0.0296</td>
<td>-0.0380</td>
<td>-0.0994</td>
</tr>
</tbody>
</table>

|        | \( \pi_t \) mean | 5.3995 | 5.4256 | 5.3968 | 5.4270 | 4.4178 | 3.9173 |
| \( \pi_t \) median | 5.1631 | 5.1602 | 4.9738 | 4.9894 | 4.0428 | 3.4877 |
| \( \pi_t \) variance | 6.0894 | 6.2343 | 5.8975 | 6.0505 | 4.7642 | 2.0190 |
| \( \pi_t \) skewness | 0.4630 | 0.4876 | 0.4977 | 0.5253 | 0.9690 | 1.0406 |
| \( \text{corr}(\pi_t, \theta_t) \) | -0.4095 | -0.9531 | -0.7056 | -0.7056 | -0.7056 | -0.7056 |
| \( \text{corr}(\pi_t, \hat{y}_t) \) | 0.0905 | 0.0802 | -0.0136 | -0.0486 | -0.0741 | 0.0891 |

|        | \( \pi_t \) mean | 2.3207 | 2.3314 | 2.3316 | 2.3405 | 2.1526 | 3.1477 |
| \( \pi_t \) median | 2.2032 | 2.2279 | 2.1992 | 2.1889 | 2.0992 | 3.0875 |
| \( \pi_t \) variance | 0.7802 | 0.7958 | 0.8222 | 0.8333 | 0.5783 | 0.7724 |
| \( \pi_t \) skewness | 0.7364 | 0.7155 | 0.8576 | 0.8082 | 0.1354 | -0.0328 |
| \( \text{corr}(\pi_t, \theta_t) \) | -0.2960 | -0.9531 | -0.7056 | -0.7056 | -0.7056 | -0.7056 |
| \( \text{corr}(\pi_t, \hat{y}_t) \) | 0.3484 | 0.3390 | 0.1707 | 0.2207 | -0.4339 | 0.5908 |

|        | \( \pi_t \) mean | 2.0393 | 2.1094 | 2.0240 | 2.1017 | 3.3201 | 1.7428 |
| \( \pi_t \) median | 2.0967 | 2.0811 | 2.0509 | 2.1373 | 3.4543 | 1.4219 |
| \( \pi_t \) variance | 0.9520 | 1.0373 | 1.1295 | 1.1798 | 0.7157 | 0.5455 |
| \( \pi_t \) skewness | -0.4800 | -0.2448 | -0.7384 | -0.5226 | -0.5588 | -0.0128 |
| \( \text{corr}(\pi_t, \theta_t) \) | 0.2980 | -0.9530 | -0.3193 | -0.3931 | 0.1237 | -0.2042 |
| \( \text{corr}(\pi_t, \hat{y}_t) \) | 0.5540 | 0.4577 | 0.4975 | 0.5322 | -0.2105 | 0.7310 |

|        | \( \pi_t \) mean | 1.6207 | 1.6196 | 1.6882 | 1.6916 | 3.1784 | 1.3842 |
| \( \pi_t \) median | 1.7169 | 1.7643 | 1.8971 | 1.9032 | 3.4464 | 1.3859 |
| \( \pi_t \) variance | 0.9074 | 0.9890 | 0.8298 | 0.8996 | 0.7946 | 0.1362 |
| \( \pi_t \) skewness | -0.5074 | -0.6060 | -0.5028 | -0.5992 | -0.1402 | -0.0915 |
| \( \text{corr}(\pi_t, \theta_t) \) | -0.7487 | -0.9096 | -0.7578 | -0.9210 | -0.8215 | -0.7935 |
| \( \text{corr}(\pi_t, \hat{y}_t) \) | 0.1297 | 0.0907 | 0.8588 | 0.8924 | -0.2886 | 0.3788 |

Note: The table shows the mean, median, variance, skewness, and correlation coefficients of inflation moments and related statistics for different periods, using a filtered non-linear model and counter-factuals.
References I


